

METAL BAND DRIVES IN SPACECRAFT MECHANISMS

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ABSTRACT

Transmitting and changing the characteristics of force and stroke is a requirement in nearly all mechanisms. Examples include changing linear to rotary motion, providing a 90° change in direction, and amplifying stroke or force. Requirements for size, weight, efficiency and reliability create unique problems in spacecraft mechanisms. Flexible metal band and cam drive systems provide powerful solutions to these problems.

Band drives, rack and pinion gears, and bell cranks are compared for effectiveness. Band drive issues are discussed including materials, bend radius, fabrication, attachment and reliability. Numerous mechanisms are shown which illustrate practical applications of band drives.

1.0 PERSPECTIVE

1.1 Approaches to changing force and stroke

Various mechanical methods can be used to change force and stroke including gears, linkages and belt drives. Appended to this paper, are scale drawings (figures 1.1.1, 1.1.2, 1.1.3) illustrating the typical layout and part sizing for transmitting a linear input of 444 N (100 lbs) over 1.9 cm (.75") into a rotary output.

1.2 Summary of effectiveness

Each of these three approaches was evaluated for its effectiveness in small compact mechanisms transmitting relatively high loads in contamination sensitive environments. They are ranked in descending order of effectiveness for each issue.

1.2.1 Size and Weight

Band- Smallest size and weight for a given load
Rack- Gear teeth strength requirements increase size
Crank- High loads require large rollers which interfere with short lever arms

1.2.2 Efficiency

Band- 96%, from loss at axle bearing
Rack- 94%, additional loss at gear teeth interface
Crank- 88%, angular input requires more sliding surfaces creating more friction

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1.2.3 Contamination

Band- Band produces no contamination
Crank- Limited to rolling surfaces
Rack- Gear teeth wear and produce particles

1.2.4 Life/wear

Band- Nearly infinite fatigue life
Crank- Higher number of sliding surfaces
Rack- Lubrication determines gear teeth life

1.2.5 Tolerance requirements

Band- Minimal
Crank- Minimal
Rack- Precision alignment of gear teeth required

1.2.6 Capability for linear to rotary transmission

Rack- Infinite angular capability
Band- 270° maximum rotation limit
Crank- 90° maximum rotation limit

1.2.7 Other limitations, advantages

Rack- Fixed output ratio, Bi-directional
Band- One direction (only pulls), variable output ratio
Crank- One direction (only pushes), variable output

2.0 DESIGNING WITH METAL BANDS

Metal band drives are easy to use. However they do have some unique design and production issues that require careful attention.

2.1 Material

The ideal metal drive band would have very high strength and a high modulus of elasticity. A thorough review of available materials and their properties led to a material with the trade name of Elgiloy. It was developed in the 1940's for watch springs. Elgiloy is a cobalt chromium nickel alloy with the following composition:

CO 39/41%
CR 19/21%
NI 14/16%
MO 6/8%
MN 1.5/2.5%
C 0.15%max
BE 0.10%max
FE balance

Elgiloy is available as strip, ribbon wire, rod and cable. Its mechanical properties are derived from a combination of cold work and subsequent heat treatment. This material processing produces thin bands with very high strength.

Ultimate tensile strength - 1,724 to 2,414 MPa (350 Kpsi)

Hardness (HRC) - 45 to 60

Elastic modulus - up to 206,910 MPa (30,000,000 psi)

Fatigue life - excellent (see fatigue, S-N curve)

Corrosion resistance - Excellent (MSFC-SPEC-250)

Stress corrosion cracking - (A rating MSFC-SPEC-522)

Compatibility - GOX, LOX, N₂O₄, HDZE, H₂

Magnetic permeability - 1.00004 at 25°C

Coefficient of thermal expansion - 15.17×10^{-6} per °C

Temperature range for normal performance - -150°C to 450°C

For comparison titanium has a tensile strength of only 827 MPa (120,000 psi) and a modulus of 114,000 MPa (16,500,000 psi).

2.2 Bend radius

Spacecraft mechanisms frequently have severe envelope restrictions. A band drive provides a good solution to these restrictions. Minimizing the overall size of a band drive can require using the smallest possible cam diameter and band bend radius. The graph shown in figure 2.2 illustrates the relationship between bend radius and yield strength for bands typically used in Starsys Research mechanisms.

We typically allocate 50% of the band yield strength to load transmission and use the remaining strength for bending stress. Final selection of bend radius, band thickness and band width can be made after assigning their relative priority in the design and band strength margin requirements. It should be noted that by simply cold forming the bands to 2x the bend radius bending stress can be reduced by 50%.

2.3 Fatigue

Elgiloy bands have excellent fatigue resistance. The S-N curve shown in figure 2.3 illustrates this.

2.4 Attachment

Mechanical methods of attachment are superior to other methods in fatigue and strength. Spot welding, soldering and brazing can be used but they weaken the material. A simple, reliable method of mechanical fastening was developed and is used in the mechanisms illustrated. The drawing shown in figure 2.4.1 is from a telescope launch lock. It illustrates both flat and radial attachments.

The geometry for attachment is shown in figure 2.4.2. The following formulas relate to the figure. Band stress at the thinnest point in the attachment is equal to the load carried divided by the sum of the width minus the hole diameter times the thickness, $S=F/(W-D) \times T$.

The length of the band end from the end of the band to the attachment hole center is ideally a minimum of 2 times the diameter. Shorter lengths have been used but they significantly reduce the load carrying capability of the attachment (see Testing).

Band bearing stress is equal to the load divided by the hole diameter times the thickness, $S=F/(D \times T)$. Because band attachment is typically sized to carry 50% of the yield stress of the band, the hole diameter should be from 1/2 to 1/3 the band width. This is consistent with allowing 50% of the absolute stress for bending.

Bearing stress of the pin on which the band bears are high. The band clamp design used induces tri-axial stress which increases the effective strength of the material. Only minor deformation has been seen with 303 stainless steel pins.

2.5 Fabrication

Because the band shape is so simple, the first band components were fabricated by conventional machining technology. The band material was clamped between two pieces of aluminum and shaped with carbide tooling. While good quality bands were produced, this method was difficult and tooling wore out quickly. Practical tolerances were limited to ± 50 microns (.002").

Because of these difficulties subsequent band components were fabricated by Wire Electrical Discharge Machining or WEDM. Starsys Research regularly uses WEDM for cutting complex shapes in electrically conductive materials. This fabrication process uses the electrical arc from a wire held at both ends and submerged in a water solution to remove material. It easily produces parts with tolerances of ± 5 microns (.0002").

Developing a process to fixture the thin band material was straight forward. After machining, minimal deburring of the edges is required. The parts produced by WEDM are of very high quality and accuracy.

2.6 Design and assembly

Metal band drives function well with easily obtained tolerances, typically $\pm .127$ mm (.005") for most mechanism parts. Attachment holes and through pins are held to ± 13 microns (.0005"). Be careful to control fillet radii of integral clamp and pin assemblies so they do not interfere with clamping.

Since the bands tend to adjust themselves to proper alignment, only normal visual alignment is required during assembly. Care must be taken to properly align and

secure attachment clamps. 2-56 and 4-40 screws were used to secure band clamps.

Metal band deformation or stretch from loads is minimal. A band loaded to 25% of its yield strength would stretch .2%.

3. FAILURE MODES AND TESTING

3.1 Attachment testing

Testing was performed to verify the performance of the band drive designs. The majority of the testing focused on band attachment. Bands were fabricated and tested to failure. The following observations summarize the testing.

- 1) When the band clamps were tight, .56 to .06 N-m (5 to 0.5 in-lb) torque, failures occurred at 91 - 83% of the design yield strength of the attachment.
- 2) When the band clamps were loose, .08 cm (.030") gap, failure occurred at 66% of the design yield strength of the attachment. Failures began with buckling of the band in the bearing area. Buckling of the band concentrated stress in adjacent areas and allowed the attachment pin to tear out of the band.

These bands had a band end length to attachment diameter ratio of 1.5 to 1.0. A longer attachment length would perform better. Testing to verify band attachment strength is highly recommended.

3.2 Corrosion

The corrosion resistance of Elgiloy is excellent, as good or better than other metals typically used on spacecraft. Its galvanic potential is cathodic or protected, similar to passivated chromium stainless steel.

3.3 Reliability/Redundancy

The reliability of single bands should be established by component testing. Redundant bands have been successfully utilized on two mechanisms. In one design, the bands were slotted on one end and therefore not constrained in motion. In the other, the bands move through two reverse radii which equalize band length.

Because of band elasticity and stretch, parallel bands will accommodate normal variations in tolerance and still distribute loads. Burnishing molydisulfide onto the band surfaces that contact each other eliminates visible abrasion and wear.

4. CONCLUSION

Metal band drives offer several advantages including; small size, high efficiency, low contamination and long life. They provide unique solutions to difficult problems for example, providing variable output from a constant input. They are straightforward to design and easy to fabricate.

Because of its high tensile strength and other properties Elgiloy is an excellent choice of material for the drive band in these mechanisms. Bands should be analyzed for bending stress and attachment design should be tested.

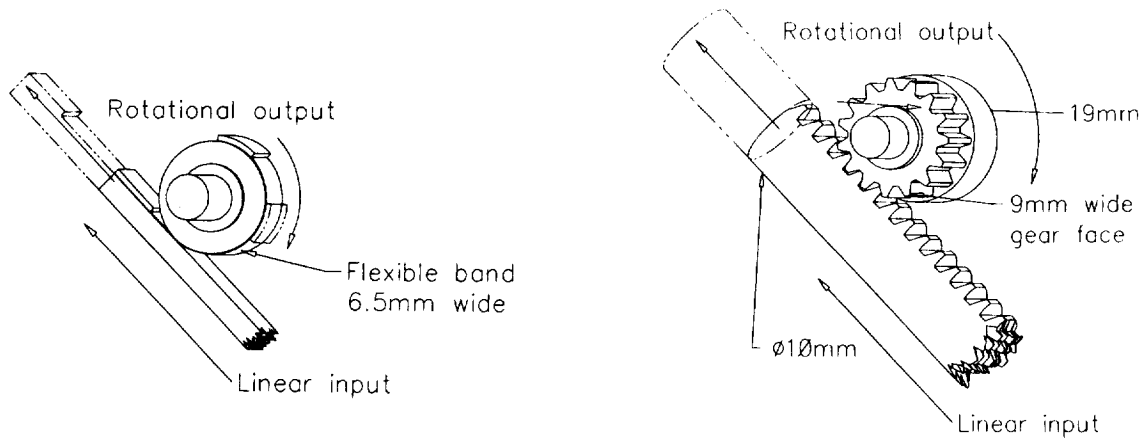


Figure 1.1.1
Belt drive - Metal band drive
Output: 3.39 Nt-m (30 in-lbs) over 137°
Efficiency: 96%

Figure 1.1.3
Gears - Rack and pinion
Output: 3.28 Nt-m (29 in-lb) over 137°
Efficiency: 93%

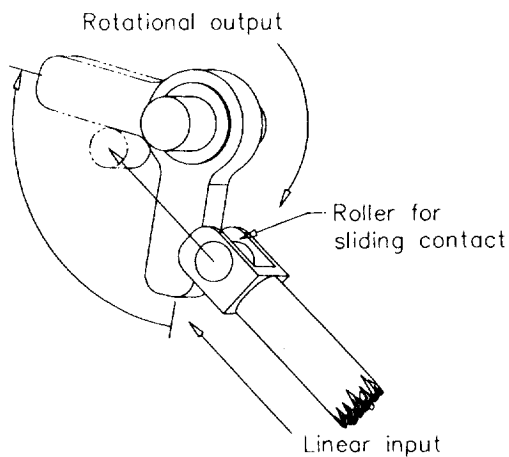


Figure 1.1.2
Linkage - Bell crank
Output: 3.73 Nt-m (33 in-lb) over 90°
(maximum efficient rotation)
Efficiency: 88%

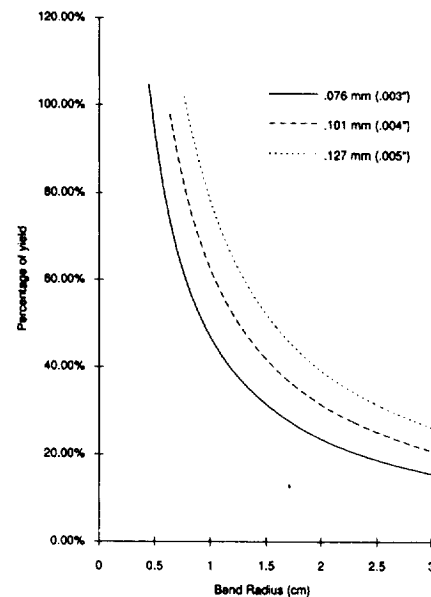


Figure 2.2
Yield strength vs. Bend radius in Elgiloy bands

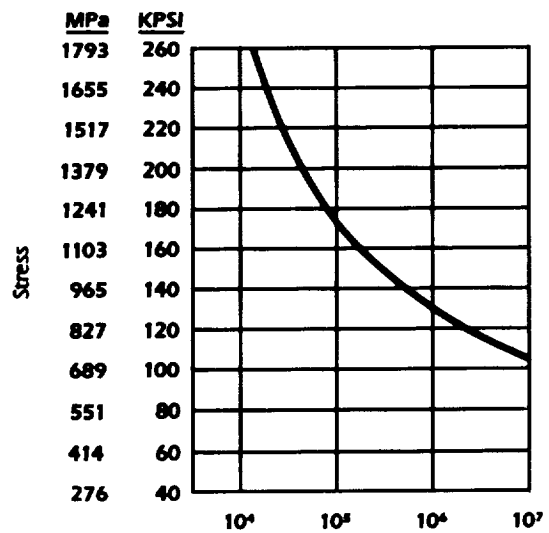


Figure 2.4.2
Band attachment geometry

4. MECHANISMS

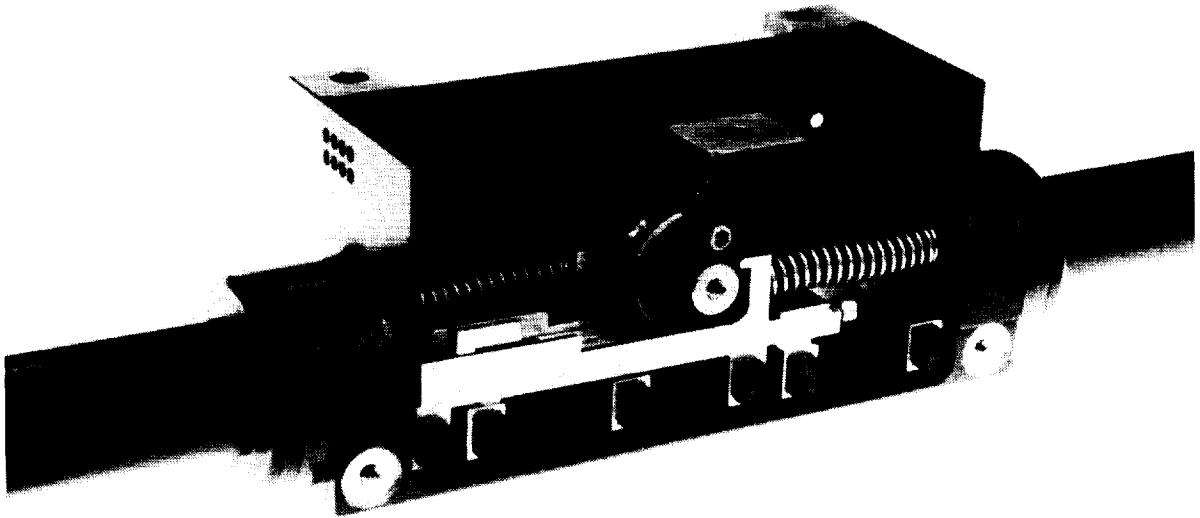


Figure 4.1 - Telescope launch lock for UVCS on SOHO-MAMA - Translates linear input to rotary output

Input: 2x 444 Nt (100 lbs) over 14 mm (.55") extension

Output: 2x 1.7 Nt-m (15 in-lb) over 90° plus latching

Bands: Two .076 mm (.003") by 6.7 mm (.265") wide

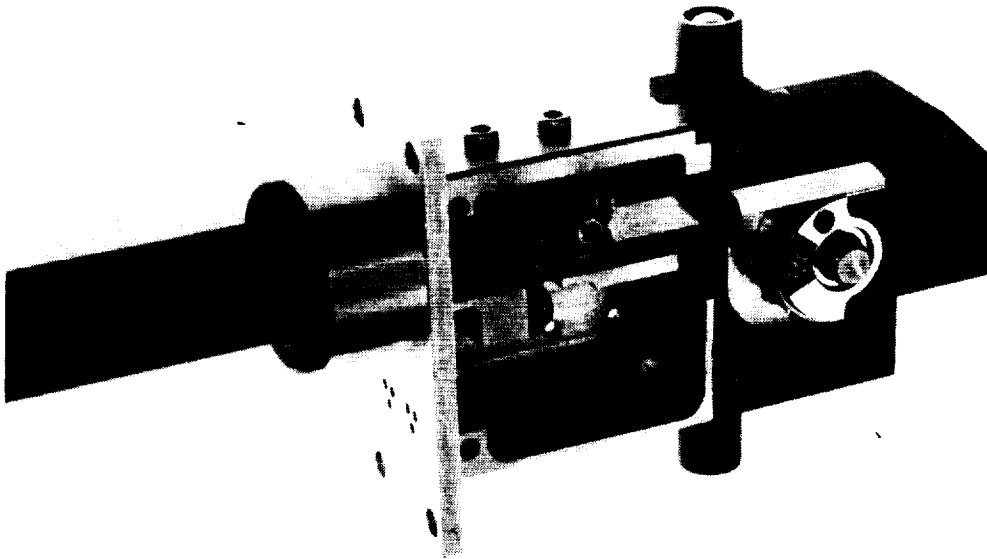


Figure 4.2 - Cover operator for UVI on POLAR - Amplifies stroke

Input: 444 Nt (100 lbs) over 14 mm (.55") extension

Output: 222 Nt (50 lbs) over 19 mm (.75") extension plus latching and spring retraction

Bands: Input .076 mm (.003") thick by 7.6mm (.300") wide, output .076 mm (.003") thick by 5.8 mm (.230") wide

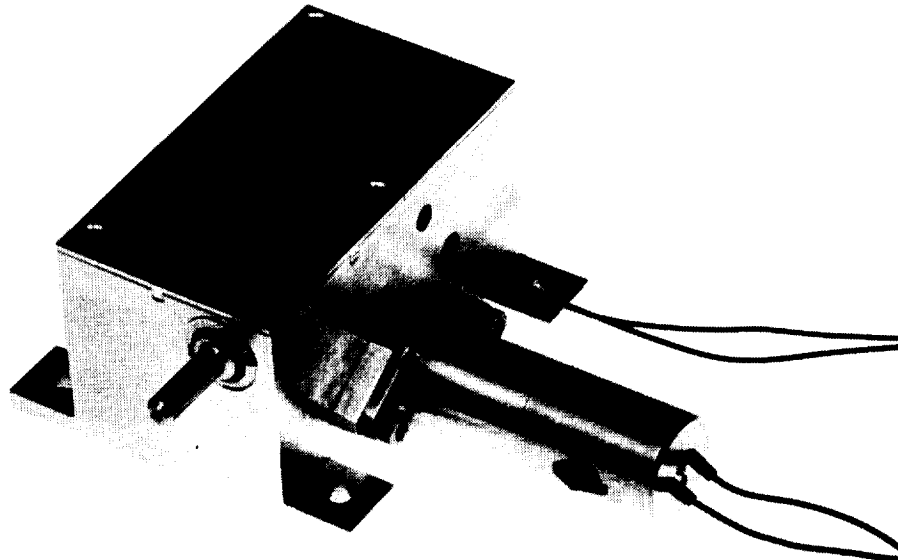


Figure 4.3 - Scan mirror lock for TIR on ASTER and launch lock for SWAN on SOHO-MAMA - Pin puller

Input: 311 Nt (70 lbs) over 6.4 mm (.25") extension
 Output: 222 Nt (50 lbs) over 8.1 mm (.32") retraction
 Bands: Two .076 mm (.003") thick by 5.7 mm (.225") wide

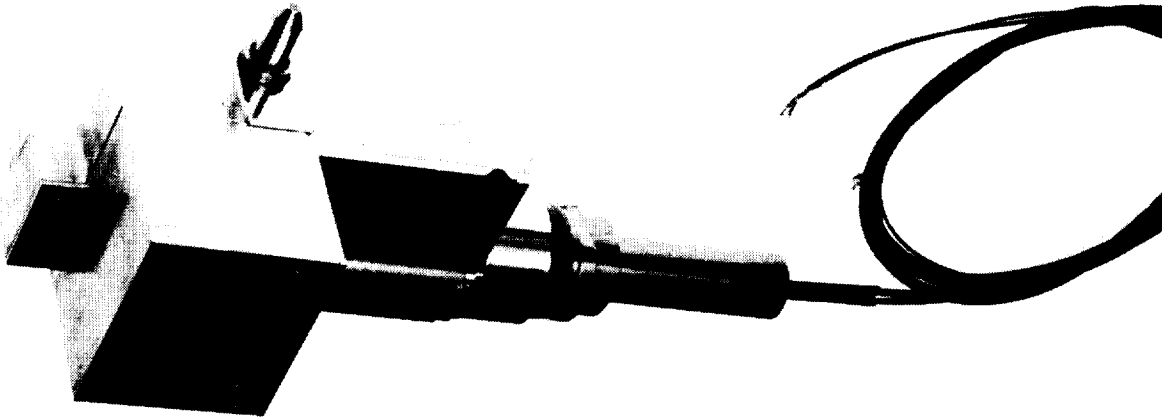


Figure 4.4 - Mirror and occulter lock for UVCS on SOHO-MAMA - Turns push into pull

Input: 444 Nt (100 lbs) over 14 mm (.55") extension
 Output: 222 Nt (50 lbs) retraction over 11 mm (.45") plus latching and spring extension
 Bands: Redundant .076 mm (.003") thick by 7.6 mm (.300") wide

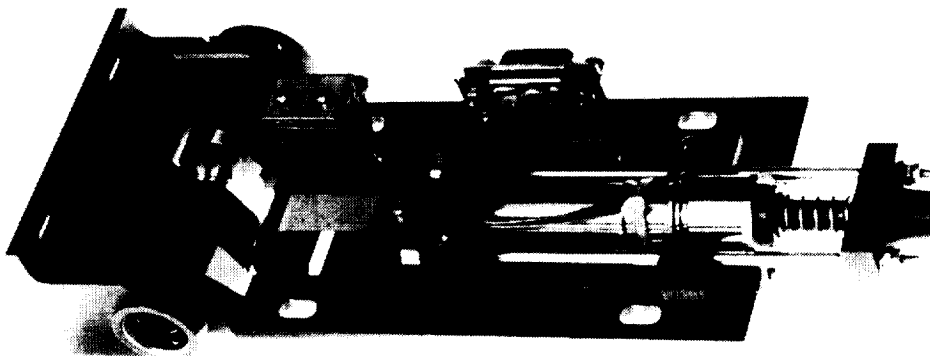


Figure 4.5- Powered hinge for APEX - Variable torque output

Input: 533 Nt (120 lbs) over 19 mm (.75") extension
 Output: 3.4 to 6.8 Nt-m (30 to 60 in-lb) over 90°
 Bands: Redundant .076 mm (.003") thick by 10 mm (.400") wide

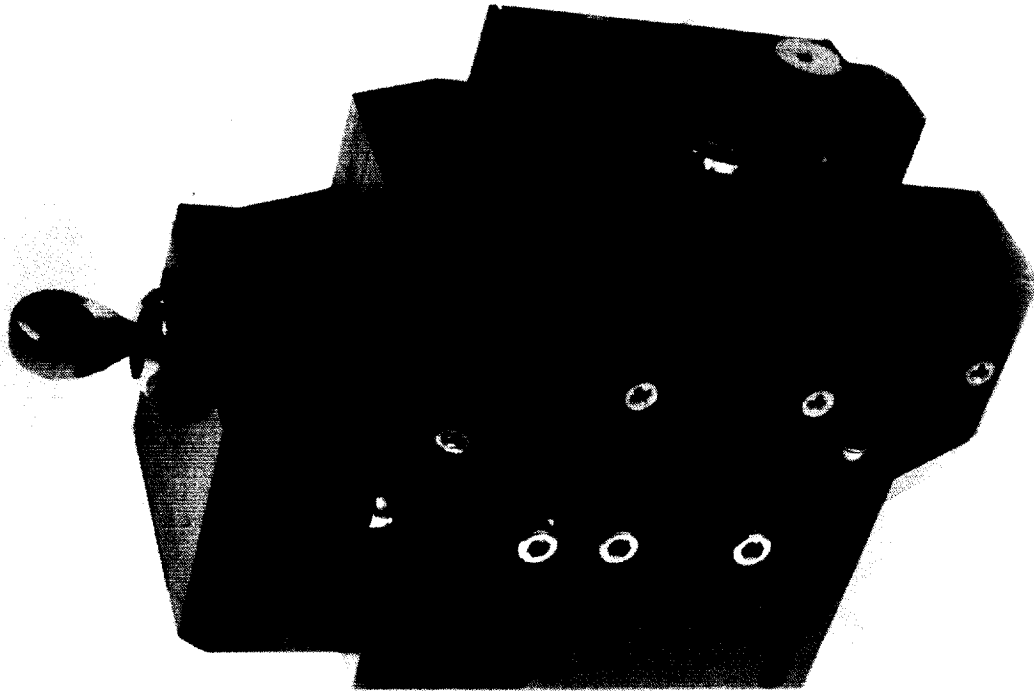


Figure 4.6- Detector cover operator for UVCS & SOHO-MAMA - Stroke doubler

Input: 2,224 Nt (500 lbs) over 16 mm (.65") extension

Output: 667 Nt (150 lbs) over 32 mm (1.25") plus latching and spring extension

Bands: Two .127 mm (.005") thick by 7.62 mm (.300") wide

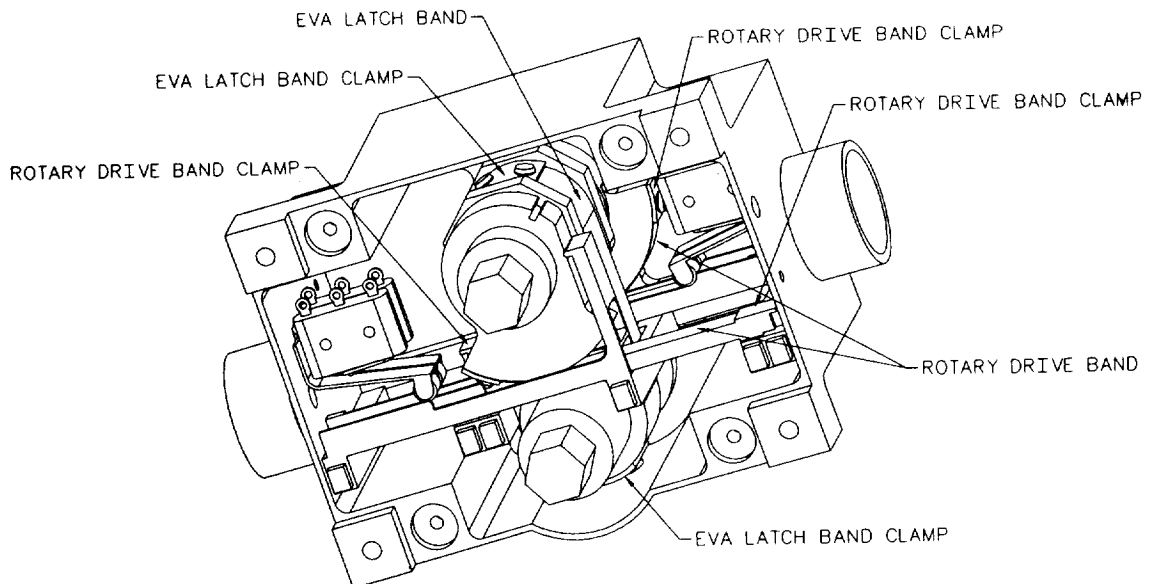


Figure 4.7 - Launch lock with EVA override for for Space Station Freedom - Rotary to rotary

Input: 2x 444 Nt (100 lbs) over 19 mm (.75") extension

Output: 2x 333 Nt (75 lbs) over 45° with EVA override

Bands: Two .127 mm (.005") thick by 6.7 mm (.265") wide and two .127 mm (.005") thick by 15 mm (.580") wide